A Conceptual Model of Groundwater Flow in the Upper Agua Fria

Elizabeth León, M.S. Student, Hydrology and Water Resources, University of Arizona
Ty Ferré, Asst. Professor, Hydrology and Water Resources, University of Arizona

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A conceptual model of groundwater flow is a qualitative framework upon which data related to subsurface hydrology can be considered. The basic components of a conceptual model are the sources of water to the region and sinks of water from the region, the physical boundaries of the region, and the distribution of hydraulic properties within the region. The formation of a conceptual model is critical to the development of a more quantitative representation of the subsurface hydrology, such as a numerical groundwater flow model. A calibrated, numerical groundwater flow model allows for prediction of the impacts of changes to the hydrologic conditions on subsurface flow. However, this requires precise definitions of the physical boundaries of the region, the water fluxes into and out of the system, and the hydraulic properties distributed throughout the region. In contrast, a conceptual model allows for general conclusions regarding the impacts of aspects of the current hydrologic conditions on current water flow directions. In addition, a conceptual model is very useful for identifying knowledge or data gaps that must be filled before a quantitative model can be constructed. The purpose of this investigation is to bring together existing hydrologic data in the form of a conceptual model of groundwater flow in the Upper Agua Fria Watershed. The final section of this document builds on our conceptual model to identify critical data gaps that currently preclude the formulation of a quantitative numerical model. Based on these data gaps, we make recommendations for preferred courses of action that will allow stakeholders within the Upper Agua Fria to monitor changes in their groundwater resources, begin to set limits on sustainable development, and begin to acquire the data that would be necessary to construct a calibrated numerical groundwater flow model.

Any groundwater flow model, whether conceptual or numerical, is a form of a water mass balance calculation. Stated simply, the amount of water added to the system in a given period of time less the water removed from the system in the same amount of time is equal to the change in the amount of water stored within the system during that time. The simplest groundwater model is a basin-wide mass balance. Water is typically added to the system as precipitation. This may be a combination of rain and snow. Water can also be added to the system as subsurface flow. Water is lost from the system through streamflow, subsurface flow, evaporation, transpiration, and human withdrawal. If the aquifers are unconfined, as is the case throughout most of the Upper Agua Fria, then the change in water stored can be determined based on changes in the water table elevation through time. More complex groundwater flow models account for the movement of water within the domain. A steady state groundwater flow model requires that the spatial distributions of water inflow and outflow as well as the subsurface hydraulic properties be defined throughout the region. These models can be used to characterize the movement of water through the subsurface if none of the input parameters discussed change in time. A transient groundwater flow model also requires that any changes in water input or output through time be defined throughout the entire region. A transient groundwater flow model can be used to characterize changes in groundwater flow due to changes in precipitation (for example due to climate change) or changes in outflow (for example due to increased pumping). The measurement of each component of a groundwater model has particular challenges. Below, those challenges are discussed in relation to forming a groundwater flow model for the Upper Agua Fria.

Water Storage

An unconfined aquifer can be visualized as a partially filled glass of water. If water is removed through a straw placed at the bottom of the glass, the overlying water flows downward to take the place of the removed water. As a result, the water level within the glass falls. The distance that the water surface drops is directly related to the amount of water removed and inversely related to the size (horizontal cross sectional area) of the glass. Now consider what happens if you fill the glass completely with ice and water. As before, if you remove water from the base of the glass, the water level falls. But, because the ice takes up much of the area that would be available for water, the water level falls much farther for a given volume of water removed. As a good approximation, the water falls farther by a factor of 1/n, where n is the ratio of the volume of the voids between the ice cubes to the total volume of the glass. The term, n, is known as the porosity. In much the same way, the change in water level throughout a region over a given time, divided by the porosity, and multiplied by the area of the region is equal to the change in volume of water stored in that time. (To be exact, the porosity has to be modified to account for a small amount of water that cannot be removed from the subsurface by drainage. Therefore, the porosity should be replaced by the specific yield.)

Generally, when we think of drinking water from a glass with a straw, we picture the water surface as falling uniformly, maintaining a flat surface. However, if we imagine the water draining from a tub, we think of the water surface forming a depression above the drain. This depression forms because the water flows into the drain faster than it can be replaced by lateral flow in the tub. The measure of the ease with which water can flow is known as the hydraulic conductivity. If the tub is filled with ice (or sand) and water, the hydraulic conductivity will decrease even further. As a result, it is even more likely that the water surface within the sand will have a depression above the drain. The same is true if water is added to the sand more rapidly than it can flow laterally: a mound will form. The combined result of the relatively low hydraulic conductivity of the subsurface materials and the distributed locations of groundwater recharge (at mountain fronts and beneath streams) and groundwater discharge (gaining stream reaches) is an irregular water table surface. This surface is further impacted by the distribution of hydraulic conductivity throughout the region.

As with the example of the tub, above, water in an unconfined aquifer generally flows from regions of high water level (the walls of the tub) to regions of low water level (above the drain). Therefore, a water table elevation map can be used directly to infer directions of groundwater flow. For this reason, the first task of this Rural Watershed Initiative program was the construction of an updated groundwater elevation map (Figure 1). Every available water table elevation was plotted on this map and then contoured manually. Groundwater flow arrows were added perpendicular to these contours. The map shows a lack of spatially distributed information, most notably the relatively small area within which there are available water table elevation measurements. This lack of data is common for relatively undeveloped areas. The majority of the available measurements were made in domestic water supply wells. The approximately 15% remaining wells were monitoring, irrigation, stock, or municipal supply wells. As a result, the measurements are largely confined to areas with higher population densities where the water table is relatively close to the ground surface. The deepest reported well depth is 723 feet below the land surface. However, 70% of the groundwater wells (164 out of 255 wells) in the Agua Fria Watershed yield water within the top 100 feet below the land surface (Figure 2). Given that we cannot define the changes in water table elevation outside of the region with good well coverage, any detailed groundwater flow model would have to be limited to a smaller region within the Upper Agua Fria (More discussion of this is presented below under Boundaries.)

It is typical that rural areas, especially those in mountainous terrain, have sparse water level measurements. However, much of the region of immediate interest (the "corridor of interest" from Cordes Junction to Mayer on Hwy 69) with regard to the impact of further development lies within the area of reasonably good well coverage. However, the mere presence of wells is not sufficient to provide data for hydrologic analysis. It is imperative that efforts be made to monitor water levels and water level changes on a regular basis as a direct measure of the impacts of changes in climate and in water demand on water resources within the Upper Agua Fria. It may also be useful to augment these measurements with regular gravity surveys to define the cumulative water storage in the subsurface throughout the watershed (Pool & Schmidt, 1997).

Hydraulic Properties

Examination of any road cut will show that natural geologic formations are highly structured and vary greatly over distances as short as a mile. The area of good well coverage within the Upper Agua Fria can be described as rectangular, approximately 17.2 miles on one side and 2.4 miles on the other side (Figure 3). The surface materials within this region vary from exposed bedrock to alluvial basin-fill material, which ranges from just a few feet to up to 300 feet thick (Wilson, 1988). The definition of spatially distributed hydraulic conductivities is one of the most challenging aspects of subsurface hydrology. While this heterogeneous distribution has greatest impacts on the movement of contaminants and other dissolved constituents through the subsurface, it also impacts the movement of water. In practice, due to a pervasive lack of data, most groundwater flow models use highly simplified descriptions of the distributed hydraulic conductivity.

Groundwater flow models can be useful predictive tools despite poor descriptions of hydraulic conductivity distributions. This is especially true if the hydraulic conductivity does not vary greatly within the region. Unfortunately, examination of drillers' logs and as stated in previous investigations, water table elevation measurements indicates that water resides predominantly within fractured rock in the Upper Agua Fria (Littin, 1981). (Exceptions to this are generally limited to regions beneath and adjacent to streams.) Fractured rock is extremely heterogeneous. Furthermore, few good measures of the hydraulic conductivity of fractured rock are available in the literature. Even these measurements must be applied with caution because it is the fracture pattern and fracture density that controls the hydraulic conductivity. It is very rare that these fracture patterns are well characterized. The fact that fractured rock aquifers underlie the Upper Agua Fria will greatly limit the ability to formulate a predictive groundwater flow model for the region.

Boundaries

The physical limits of the region under consideration must be defined in order to construct any groundwater flow model. By definition, water is added to (or removed from) the region when it crosses one of these boundaries. For hydrologic analysis, these boundaries are characterized as one of two types. For the first boundary type, the water table elevation at the boundary (more precisely, the potential energy of the water at the boundary) is defined as a function of time. For the second boundary type, the flux of water across the boundary is defined as a function of time. To return to the analogy of a drinking glass, the bottom and sides are constant (zero) flux boundaries. As water is added to (or removed from) the system the water pressure may change at these boundaries, but the flux across them will always be zero. If water evaporates from the glass at a constant rate (or is withdrawn through a straw) then the top boundary (or the portion of it pierced by the straw) can be represented as a specified flux boundary. This flux may vary with time. Then, the potential energy at the top boundary (represented as the water level) will change with time in response to the rate at which water is removed. Alternatively, the water level could be measured frequently and the water level as a function of time could be “defined” on the boundary. Then the flux across this specified head boundary could be determined as a function of time.

Groundwater flow models typically have upper, lateral, and lower boundaries. The upper boundary is often taken to be the ground surface. The ground surface can be characterized as a specified flux boundary in areas where water infiltrates across the water table or where water leaves the subsurface as springs or through plant uptake. Alternatively, measured water table elevations can be used to define the potential energy at the upper surface. In reality, all of these upper boundaries actually represent the water table more accurately than they represent the ground surface. But, this distinction is not important for this discussion. Lateral boundaries are often the most difficult to define. Some physical boundaries can be used. For instance, a water table divide can be defined as a zero flux boundary. A stream can be defined as a specified head boundary. In the case of the Upper Agua Fria, we use the Big Bug Creek and the Agua Fria River as two lateral boundaries of our model domain (purple line in Figures 3 & 5). The groundwater divides in the Upper Agua Fria Watershed; if they can be presumed to lie near the tops of the mountain ridges, lie far outside of the area that is well characterized by water table elevation measurements. In cases such as this, it is common to assign approximate boundaries based on a water table elevation map. For instance, the long lateral boundaries shown on Figures 1, 3, 4, & 5 were chosen to lie along the rivers. These boundaries can be approximated as no flow boundaries. The shorter lateral boundaries lie along equipotential lines and are represented as specified head boundaries. These boundary conditions will not be appropriate for modeling the impacts of severe changes to the hydrologic conditions such as sustained climate change or significantly increased pumping. The lower boundary of a model is often the easiest to define. Many aquifers are comprised of alluvial material overlying bedrock (fractured or unfractured). Because the hydraulic conductivity of the alluvium is so much higher than that of the bedrock, it is common to set the bedrock contact as a zero flux bottom boundary. Unfortunately, the hydraulic conductivity of the fractured rock aquifers that characterize much of the Upper Agua Fria likely transitions smoothly to the very low hydraulic conductivity of the underlying unfractured bedrock. As a result, the location of the lower boundary (and the variation of hydraulic conductivity with depth) will vary in an unknown way, adding further uncertainty to a numerical groundwater flow model.

Sources of Water

The primary control on the rate and patterns of subsurface water flow are the rate and distribution of water supply to (and water withdrawal from) the region. In the simplest analysis, sustainable water withdrawal within a region cannot exceed the amount of water that is provided to the region. This is the maximum water withdrawal that can be sustained; although compelling arguments exist to suggest that sustainable withdrawal will be much lower. In addition to using a description of the distribution and rate of recharge to address questions of water supply, this information can be helpful for protecting groundwater quality. Specifically, if areas can be identified that are more likely to contribute recharge to the subsurface, they should be given special protection from potential sources of contamination.

The second part of this Rural Watershed Initiative project sought to identify areas that are more likely to provide recharge to the aquifer underlying the Upper Agua Fria. The analysis was based on the approach used by Alan Flint, of the United States Geologic Survey, in creating his Basin Characterization Model (e.g. Faust, 2003). Specifically, areas with thin coverage of low field capacity soils were identified as particularly likely to allow precipitation to become excess water available for potential recharge. Identified areas that also have underlying bedrock with a relatively high hydraulic conductivity are likely to produce recharge given sufficient precipitation. Precipitation throughout the watershed was defined as the mean monthly precipitation for the years between 1961and 1990 using the Parameter-elevation Regressions on Independent Slopes Model (PRISM) through the USDA Natural Resources Conservation Service and Oregon State University (Daley et al., 1997). Those regions with relatively high precipitation and relatively high likelihood of permitting recharge were identified as more likely to contribute water to the aquifer. Finally, all areas within 200 meters of a streambed were identified as areas with potentially high rates of recharge to account for current uncertainties in the contribution of streambed recharge to basin total recharge in semi-arid environments.

While we feel that the map produced for this study (Figures 4&5) represents a significant advance in the understanding of water resources within the Upper Agua Fria, we readily acknowledge that many limitations underlie this analysis. Firstly, and of greatest potential significance, the amount of water that is actually available for recharge is the difference between precipitation and evapotranspiration (water lost through evaporation and transpiration by plants). If evapotranspiration exceeds precipitation, which is common in arid and semi-arid regions, no water will be available for recharge. Unfortunately no data are available to describe evapotranspiration within the Upper Agua Fria. This major data gap will need to be filled before any water balance can be completed for the region. Secondly, recharge beneath streams must be characterized more completely to allow for integration of surface and subsurface hydrologic measurements. This can be achieved most readily through stream gauging to identify regions of gaining and losing streams and to quantify channel loss. This will be difficult, given the predominantly ephemeral nature of many streams in the region (Barnett et al., 2002). However, measurements of streamflow are critical to forming baseline hydrologic characterizations and to monitoring any potential impacts of climate change or increased water use. Finally, improved use of water balance information in arid and semi-arid regions awaits improved general understanding of the nature of groundwater recharge. Specifically, the relative contributions of slow continual recharge and rapid, event-based recharge are still unknown. Similarly, the relative contributions of mountain front, mountain block, and streambed recharge are not well understood. Continuing scientific advances in these areas should help rural communities to set priorities for data gathering for water resource evaluation.

Sinks of Water

Through uptake of water from the soil and even from below shallow water tables, plants can represent a major sink of water. As discussed above, this outflow must be characterized before a quantitative water balance can be completed. It is very uncommon for hydrologic models to include the spatial distribution of evapotranspiration when predicting water movement at the basin scale. However, with advances in computing power, GIS interfaces, and remote sensing this limitation is being addressed. In the near future, standard groundwater flow models will likely include some representation of evapotransipirative loss. Ongoing research by Dr. Tom Maddock and others at the University of Arizona, and elsewhere, continues to refine predictions of this water flux from ground based or satellite based measurements. Therefore, it would be worthwhile to begin collecting data that could be used to quantify this outflux. This could be achieved through the collection of meteorological and plant community data throughout the region.

The Agua Fria River represents a major outflow of water from the region characterized by good well coverage (Figure 1). Continuing stream gauging (see Figure 6) at or near the boundary of the domain would provide necessary data for model construction and calibration (Figures 7 & 8). In addition, as described above, these data would provide a direct measure of hydrologic changes in response to climate change or increased water withdrawal.

If the impacts of future development are of particular interest to local stakeholders, it is imperative that current and future water withdrawals be monitored. These data are necessary for water balance calculations. They are also critical for the prediction of impacts of future hydrologic changes on regions within the Upper Agua Fria. Unlike plants, which withdraw small amounts of water over large areas, pumped wells can have rather large impacts in highly localized areas. Records of static water levels within and surrounding new wells or wells that are pumped at higher rates are needed to identify the impacts of these water use changes.

Conceptual Model of Water Flow in the Upper Agua Fria

Based on the limited data available, we have developed a simple conceptual model of water flow through the Upper Agua Fria. In developing this model, we have had to make a number of simplifying assumptions. We assume that the subsurface is homogeneous and isotropic and that flow can be represented as two dimensional and lateral. We assume that the water table elevations used to create Figure 1 are representative of current conditions. We also assume that the areas identified as more likely to produce recharge are correct (Figure 4). In addition, we limit our analysis to a small region within the Upper Agua Fria, shown as an approximately rectangular area on Figures 1, 3, 4, & 5. We limit ourselves to this region because it is the only region that has sufficient well coverage to allow for the possible construction of a more quantitative, calibrated model in the foreseeable future and because it is was defined as the corridor of interest by the Upper Agua Fria Watershed Partnership. Within these limitations, we see flow as originating in the northwest from the Mingus Mountains. The Agua Fria River forms a water table divide along the northeastern boundary of the area. Groundwater flow is largely parallel to the front of the Bradshaw Mountains along the southwest boundary. The southeastern boundary experiences outflows south along the Agua Fria River near Cordes Junction. The rate of subsurface outflow cannot be determined without improved estimates of the hydraulic conductivity and aquifer thickness along this boundary. Within this area, there are two regions that are likely to produce in-situ recharge. Two extensive regions may receive recharge (Figure 5), whereas the majority of the area is unlikely to have any in-place recharge. Significant data gaps will have to be filled to transform this simple conceptual model to a quantitative numerical model. However, the formation of a semi-quantitative water balance model based on this conceptual model is achievable without impractical efforts.

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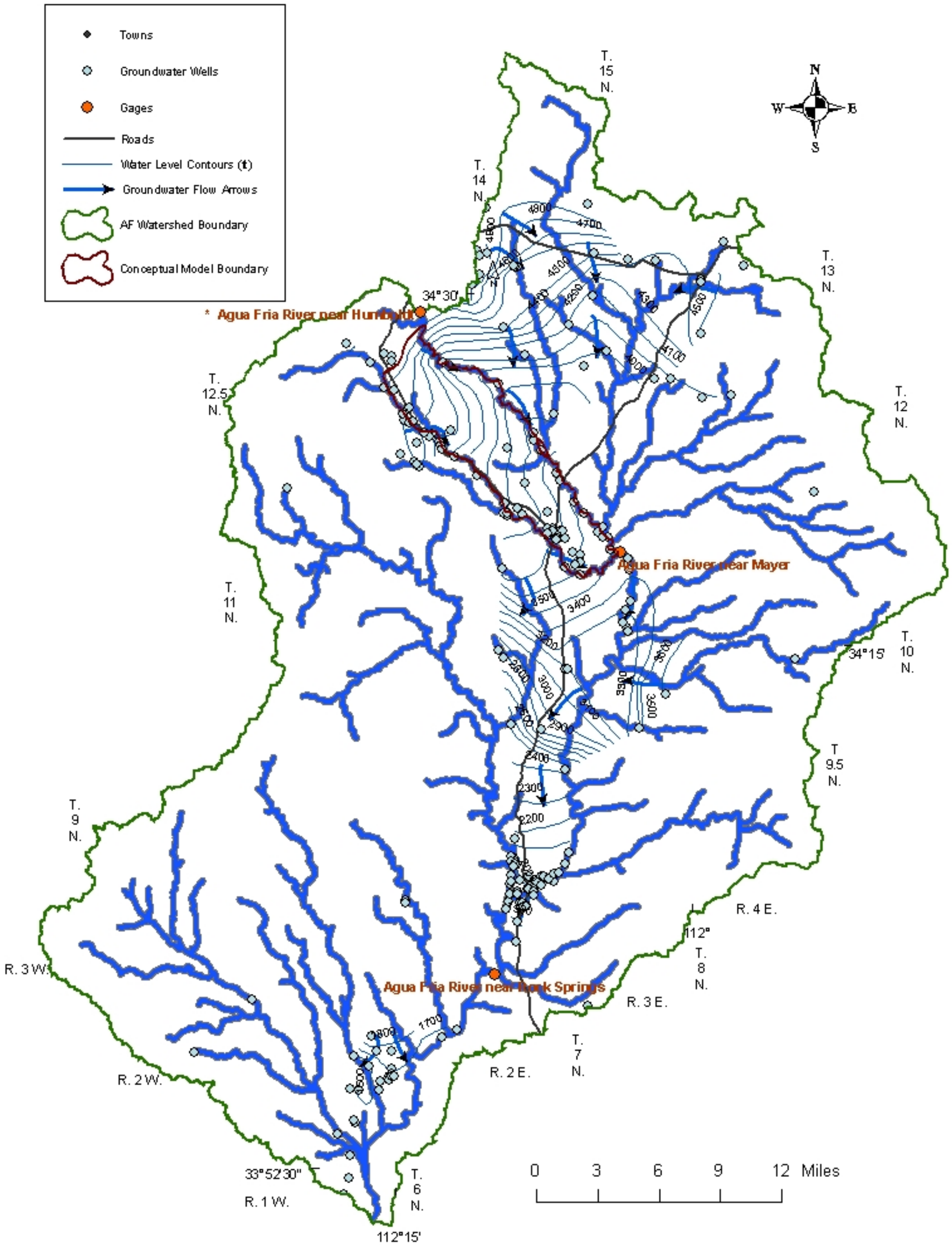

Figure 1. Potentiometric surface of the Agua Fria Watershed showing groundwater flow directions and major streams and rivers

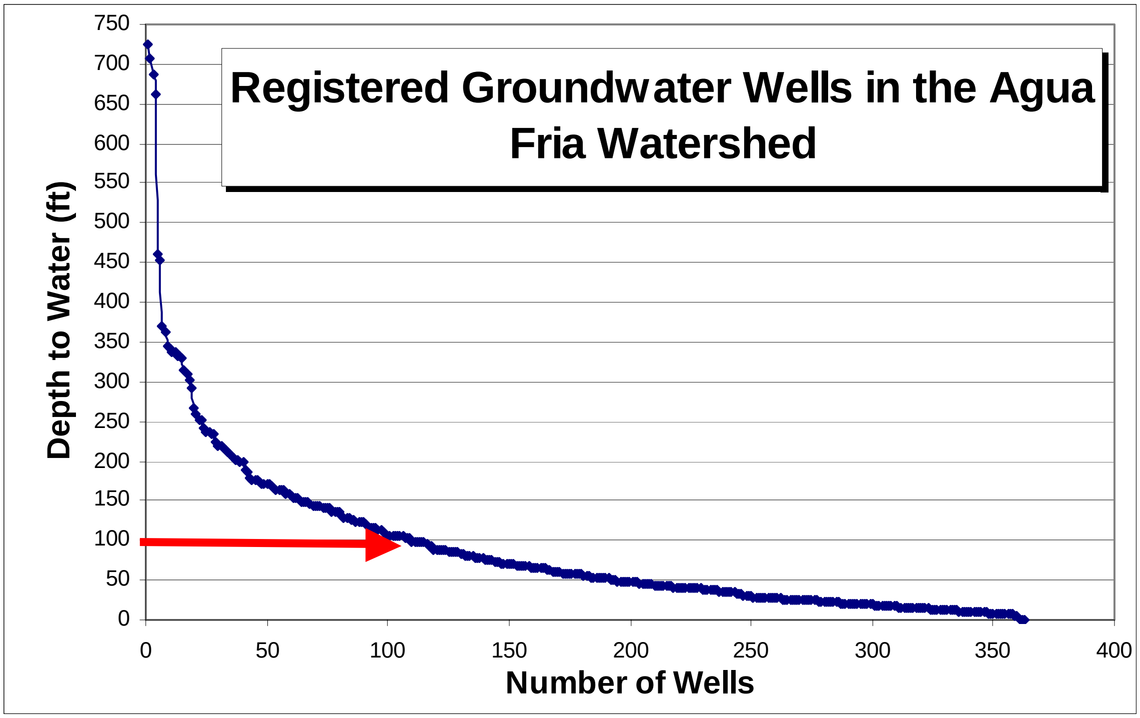

Figure 2. Groundwater wells located within the Agua Fria Watershed that are registered with ADWR, ranked in order of decreasing depth to water. The red arrow shows those wells that yield water from a depth of 100 feet or less

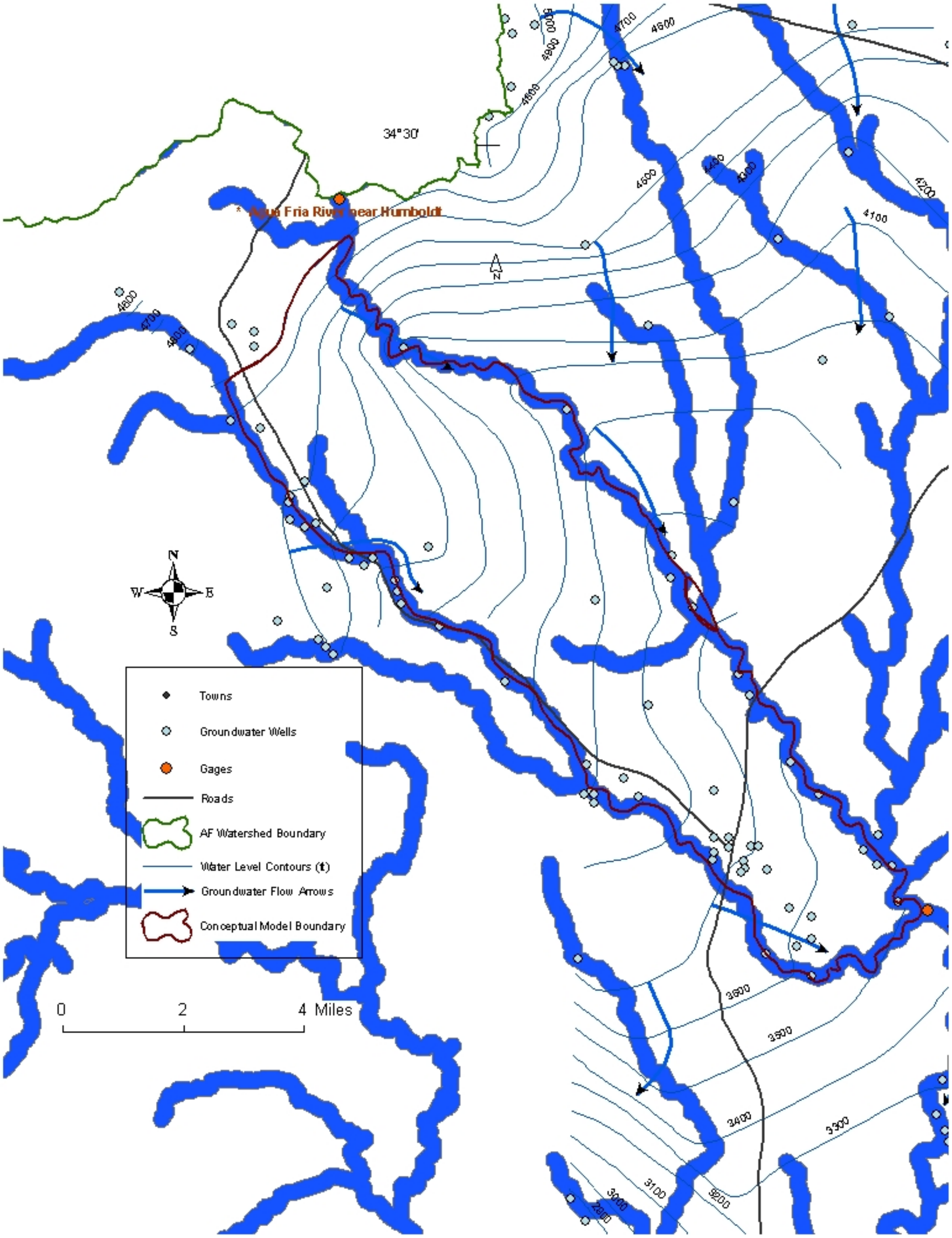

Figure 3. Detail of the conceptual model boundary and the corridor of interest shown on Figure 1

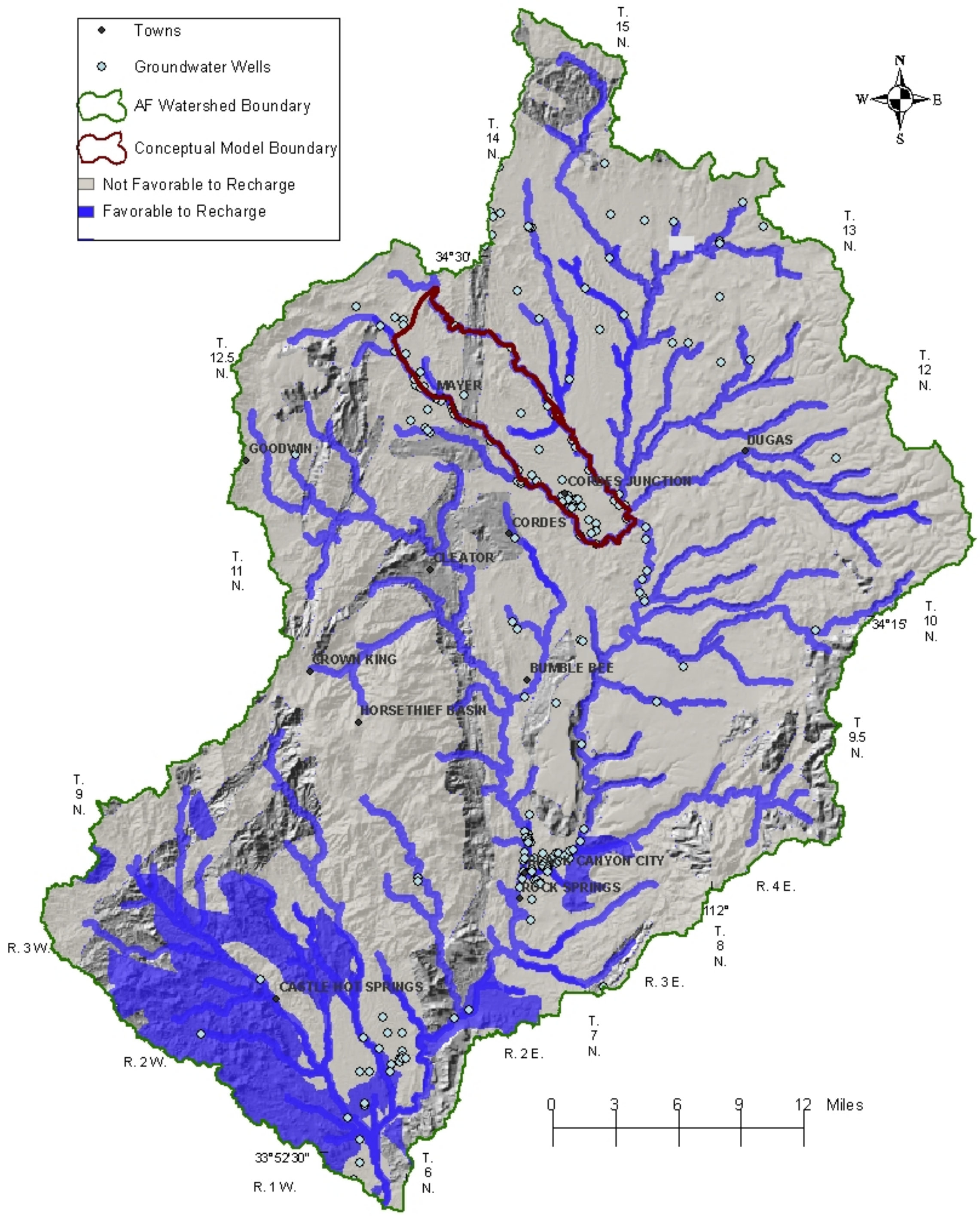

Figure 4. Likelihood of recharge within the Agua Fria Watershed

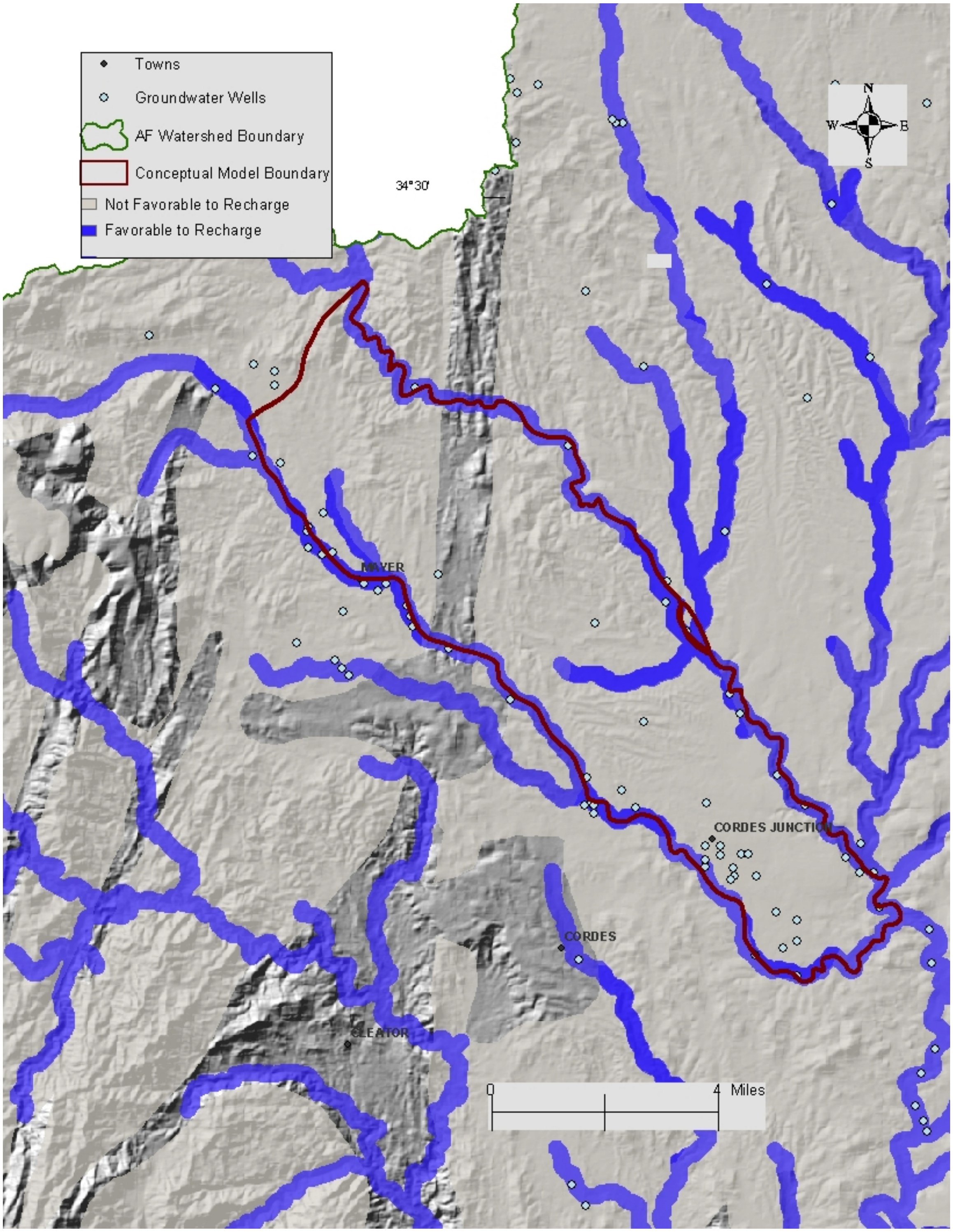

Figure 5. Detail of the conceptual model boundary and the corridor of interest from Figure 4

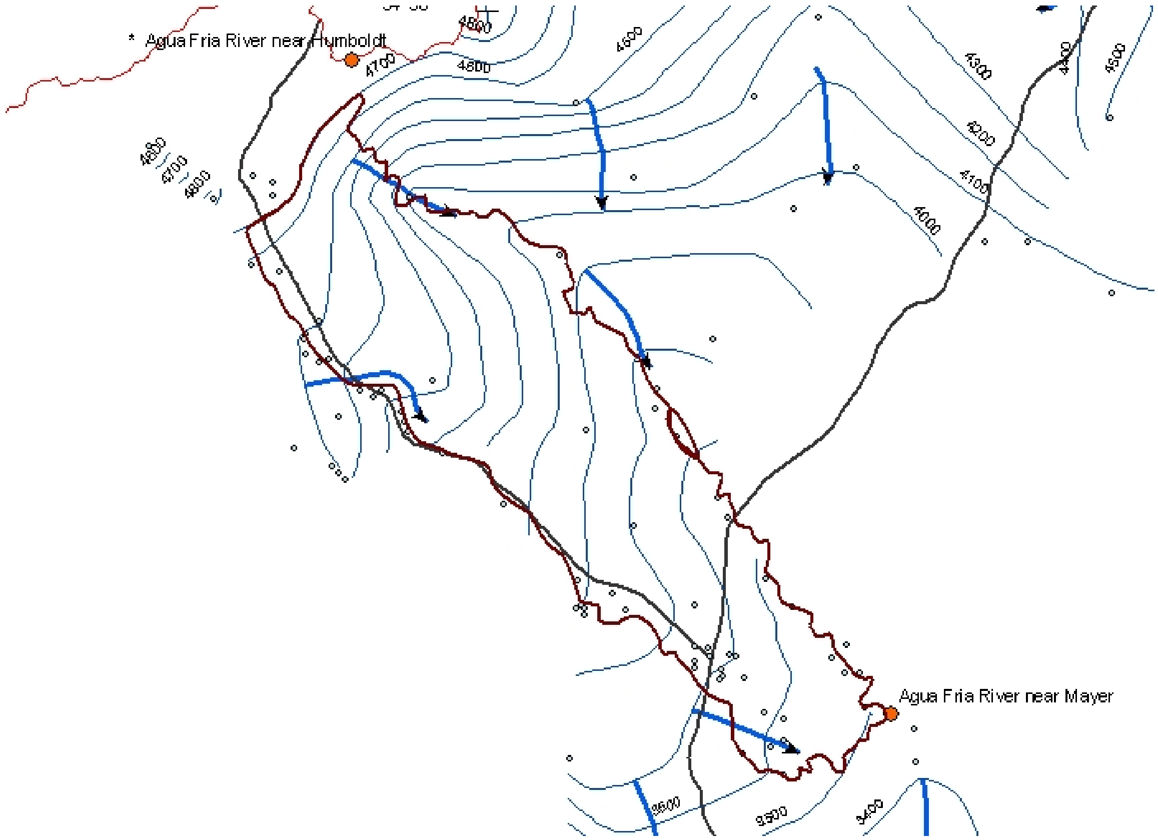

Figure 6. USGS stream gages located in the Upper Agua Fria Watershed

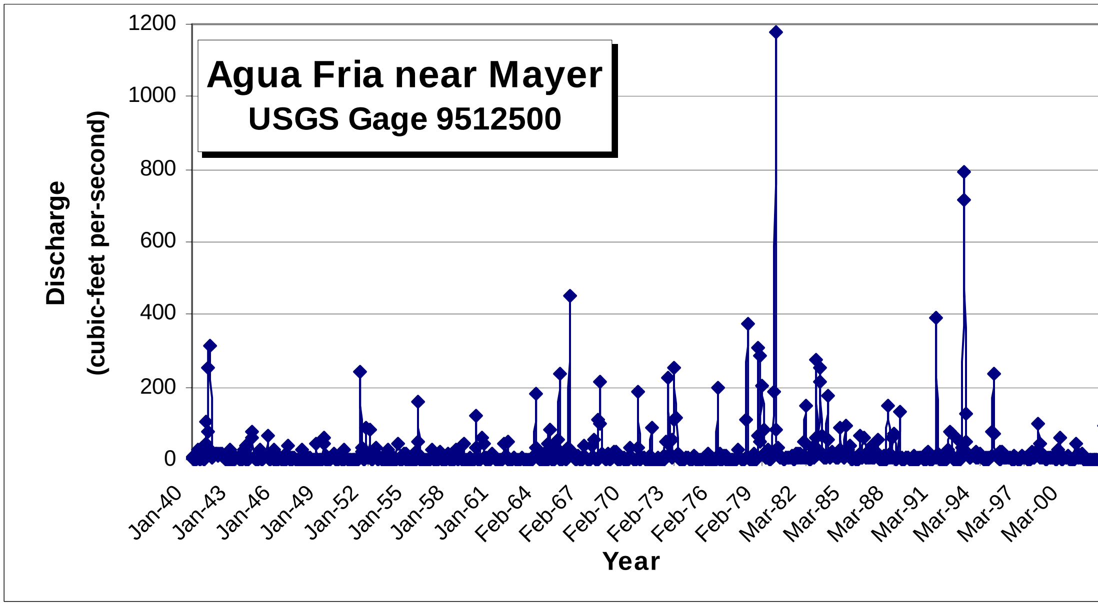

Figure 7. Hydrograph of the streamgage on the Agua Fria river near Mayer, Arizona

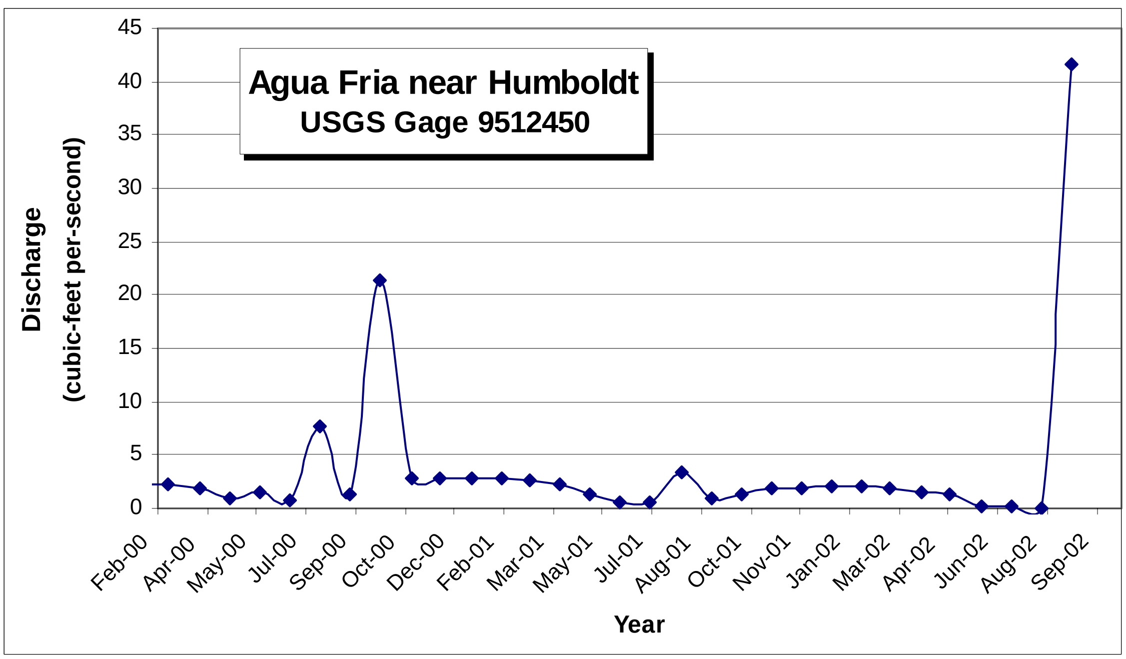

Figure 8. Hydrograph of the streamgage on the Agua Fria river near Humboldt, Arizona

Recommended Data Collection Activities to Support the Development of a Water Balance Model or a Numerical Groundwater Flow Model for the Upper Agua Fria

Elizabeth León, M.S. Student, Hydrology and Water Resources, University of Arizona
Ty Ferré, Asst. Professor, Hydrology and Water Resources, University of Arizona

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As discussed in our report, "A Conceptual Model of Groundwater Flow in the Upper Agua Fria", the subsurface hydrogeology of the Upper Agua Fria watershed will make the formulation of a predictive, numerical groundwater flow model very difficult. Critical data gaps that currently preclude the formulation of a quantitative numerical model include limited knowledge of hydraulic conductivities, especially in fractured rock aquifers; limited understanding of the contribution of streambed infiltration to total recharge; and limited measurement of hydroclimatological data. Based on these data gaps, we make recommendations for preferred courses of action that will allow stakeholders within the Upper Agua Fria to monitor changes in their groundwater resources, begin to set limits on sustainable development, and begin to acquire the data that would be necessary to construct a calibrated numerical groundwater flow model.

We recommend a path that stakeholders could follow to aid in the development of a water balance model and eventually a numerical groundwater flow model. We recommend that primary efforts be aimed at the former, because it requires far less data and is not subject to some of the serious data and process understanding limitations that face the latter. However, if a predictive model of the impacts of water use changes is desired, a numerical model will, eventually, have to be developed. In our opinion, the development of the numerical model will benefit from the efforts expended to form the water balance model.

Specific measurement and monitoring activities are listed below in order of decreasing utility and availability. That is, the first items on the list are both useful and practically achievable. The latter items are either less important for characterizing the water resources or are much more difficult to obtain.

1. Annually updated water table elevation maps,
2. Ground-based precipitation and hydrometeorological monitoring,
3. Estimates of evapotranspirative demand,
4. Measurement of stream channel loss, flow extent, and flow duration,
5. Basin-wide measurements of changes in subsurface water storage,
6. Pumping test analyses of current and future pumped wells,
7. Characterization of hydraulic properties of fractured rock regions.

Monitoring changes in the water table elevation (1), both locally and throughout the watershed, will provide the most direct evidence of changes in water resources due to changes in water use. While this measure does not always provide a quantitative link between increased pumping in one location and water level changes in another, it can serve as a warning that water use changes are having a potentially lasting effect on the local or watershed-wide water resources. The GIS-based water table elevation map produced under this project provides a very convenient format for updating these measurements. It is preferable that these measurements be made at least once per year to serve as an early warning measurement. The measurements should be made at the same time of year to avoid misinterpretation of seasonal effects. The conservative approach, from the point of view of protecting groundwater resources, is to make the measurement when the water level is expected to be at its lowest. Existing well records should be examined to choose this time.

The water balance approach used under this project to identify areas of potential recharge provides a powerful tool for assessing potential water resources. However, this model requires accurate input to accurately assess the water balance. Specifically, ground-based precipitation (1) and hydrometeorological [windspeed, temperature, and incident solar radiation (2)] measurements can greatly improve the accuracy of the input parameters needed to use this model. In addition, water uptake by plants can play a critical role in the water balance of semi-arid watersheds. Improved mapping of vegetation type and density, together with better estimates of the evapotranspirative demand of resident plant species (3) can further improve the accuracy of water balance models. Dr. Alan Flint of the United States Geological Survey can provide more information regarding the quantitative use of this model for groundwater resource analysis, and Dr. Tom Maddock of the University of Arizona can provide information regarding improved representation of plant uptake in numerical flow models. Results of such a model can give an estimate of the cumulative recharge to the aquifers beneath the Upper Agua Fria watershed. This provides an upper limit on the total sustainable water use. In addition, the spatially distributed recharge estimates provided by this model can be used as input to a quantitative groundwater flow model.

It is believed that recharge takes place through four pathways: through fractures in the mountain block with subsequent flow to aquifers; in alluvial fans at the base of the mountains; within streambeds; and distributed on the basin floor. Mountain block recharge is difficult to assess because it occurs through fractured rock and is, therefore, difficult to measure directly. Mountain front recharge can be assessed using gravity measurements or traditional methods based on piezometers, if available. Basin floor recharge can be estimated using the water balance model used in this investigation. Although it is relatively simple to measure, streambed recharge is still poorly characterized. The easiest approach to measuring streambed recharge is through measurement of channel losses during flow (4). This requires that the streamflow be measured at several locations along a stream within a short time. A downstream decrease in flow is attributed to recharge through the bed between the measurement locations. While conceptually simple, and requiring minimal instrumentation, this approach is time consuming and can be unsafe for untrained volunteers. We encourage local stakeholders to contact researchers at the Arizona universities to determine whether nominal funding could be provided to help support stream gaging by students as part of summer field courses.

Don Pool and other scientists at the United States Geological Survey, Arizona District office, have extensive experience with the use of basin-wide gravity measurements for the assessment of changes in subsurface water storage (5). These measurements rely on the changes in subsurface mass associated with filling or draining of pores in the unsaturated zone above an unconfined aquifer. Given that most of the aquifers in the Upper Agua Fria appear to be unconfined, this method would be suitable for reconnaissance mapping. In addition, these measurements can be used together with well records to assess the specific yield aquifers. This will be especially useful for the eventual construction of a numerical groundwater flow model for the watershed.

A calibrated groundwater flow model will require estimates of the hydraulic conductivity throughout the watershed. This property can, to some degree, be inferred through inverse numerical modeling of well records. However, the accuracy of the final model will be greatly improved if some direct measurements of hydraulic conductivity are available to constrain the inverted values (6). Hydraulic conductivity can be determined in a single well through slug or bail tests. This is a standard procedure whereby water is added to (or removed from) a well and the rate of recovery of the water level in the well is measured. The recovery response can be used to infer the hydraulic conductivity of the materials adjacent to the well screen, provided that well completion details are known. It is possible that such tests have been performed on some existing wells in the watershed. Collection of these data would be the least costly means by which these data could be collected. It would also be useful to request or require that all new wells be tested to provide estimates of hydraulic conductivity. Furthermore, slug or bail tests could be performed on existing wells that have not been tested. However, if the condition of the screen of an older well is in question, the results may be of limited value. Finally, a more expensive, but more broadly representative measure of subsurface hydraulic properties can be achieved through pumping tests in existing and newly drilled wells. These tests require that water be extracted from a well using a pump at a sufficiently high rate to cause significant drawdown in the pumped well and, commonly, in nearby monitoring wells. The complexity of completing and interpreting a pumping test in an unconfined aquifer would probably require that this activity be contracted to a state or private consulting organization.

The flow of water and movement of solutes through fractured rock aquifers is an area of active research. It is likely beyond the scope of any efforts that could be practically performed in this rural watershed to characterize the fracture distribution for use in a quantitative groundwater flow model (7). Rather, the best that can be achieved is to treat the fractured material as an equivalent porous medium. Then, its hydraulic properties can be assessed based on pumping tests, as described above. It would be useful, however, to collect any data that may be available concerning the depth of fracturing. These data, possible available from well logs or other geologic investigations, may allow for the definition of a no flux lower boundary of a numerical model.